EVOLUTIONARY MODEL UNCERTAINTIES IN THE K-BAND HUBBLE DIAGRAM

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ABSTRACT We explore the effects of variations in evolutionary model parameters on the K-band Hubble diagram, and compare the predictions of the older and the newer population synthesis models. The predictions of the old and the new Bruzual models differ significantly; this is tractable to a problem in combining the input stellar libraries. The new models are sensitive to a number of evolutionary parameters, and there is some coupling with the cosmological parameters. Therefore, the K-band Hubble diagram still cannot be used as a reliable cosmological tool with the state-of-the-art evolutionary population synthesis models.

The Hubble diagram is a classical cosmological test (Sandage 1988), and the last refuge of scoundrels (Lilly 1989, private communication). There is now a revival of interest in it, spurned by the recent discoveries of galaxies at redshifts where the cosmological effects should become noticeable, and by the advances in the infra-red observing technology. Samples of radio galaxies are now complete out to $z \sim 2.5$ and reach up to $z \simeq 3.8$, and even though these objects are highly unusual, they give us some glimpses about the behaviour of galaxies at large look-back times. Optically selected BCM's are known up to $z = 0.92$. The differences between $q_0 = 0$ and $q_0 = 1/2$ models in that redshift regime may be $0.7 - 1$ mag, not including the K-corrections.

Studies of radio galaxies have shown that the evolutionary effects in the visible bands dominate over the cosmological differences by several magnitudes at such large look-back times. The uncertainties of evolutionary models and their interpretation make it impossible to use Hubble diagrams in the visible regime as a viable cosmological tool. These difficulties arise mainly because the data in the observed visible light probe the rest-frame UV, which is dominated by young stars whose short lifetimes reflect and amplify any changes in the star formation rate (SFR); fluctuations in the upper end of the IMF and intrinsic extinction differences in these galaxies only worsen the situation. In addition, non-thermal light contributions in the rest-frame UV may be important. For low mass stars, which are the progenitors of red giants, and which dominate in numbers and are thus less sensitive to the fluctuations of the IMF, the relevant time scales are long (a few Gyr), and any flicker or even a long-term change in the SFR is smoothed/convolved with the stellar evolutionary time scales.

IR imaging/photometry should sample these relatively old stellar populations in distant galaxies, which change slowly. The IR magnitudes are thus potentially a robust estimator of galaxy luminosity at large look-back times. This has been tentatively confirmed by the IR data available so far: the K-band Hubble diagrams appeared to be remarkably insensitive to all the parameters of evolutionary models by Bruzual (1983), but retained their sensitivity to cosmology (Spinrad and Djorgovski 1987). Thus it was hoped that it may be possible to use distant galaxies in the near-IR as "standardizable candles". It is still too early to do this: the cosmology will have to wait for well-understood samples of high-redshift galaxies, and for more reliable population synthesis models which will account better for post-giant branch evolution and metallicity effects. However, we can make at least preliminary studies of the IR Hubble diagram.

Our first goal is to understand the near-IR Hubble diagram from the operational/procedural and theoretical points of view, without actually attempting serious measurements of cosmological parameters. We explore the sensitivity of the K-band Hubble diagram on the evolutionary model parameters, using the available K-band magnitudes of BCM's and radio galaxies from the literature as a representative data set. The purpose of this investigation is to locate the most critical evolutionary input parameters, which need to be better determined before the diagram can be used as a cosmological tool. We are *not* trying to determine the evolutionary and cosmological parameters yet – the data are not sufficiently well understood. We plan to explore the effects of dynamical evolution, selection effects and possible correlations of IR and radio luminosities at large redshifts in future papers.

A new version of Bruzual galaxy spectral evolutionary models was used to derive predictions for the K magnitudes vs. redshift. The stellar library used in Bruzual's (1983) original models was modified in the optical and IR ranges in order to build an improved set of evolutionary models. In the optical range (3600 - 10000 Å) the stellar SED's were taken from the Gunn and Stryker (1983) library. The KAO spectral library of Strecker and collaborators (1986, private communication) was used to complete the stellar SED's from 1 to 2.56 μm with 0.02 μm resolution. The matching of the IR and optical SED's was performed by means of standard relationships (Bruzual and Persson 1989, in preparation). In the UV range we used the same stellar SED's as in Bruzual (1983). The overall properties of the new set of models are similar to that of the original models. However, in the IR, the new models represent a considerable improvement over the previous ones, which only included broad band fluxes in this range. The predictions for the IR properties of galaxies derived from the new models should thus be more reliable.

As a working sample of objects, we use the available data on 3CR and 1-Jy radio galaxies, and optically selected brightest cluster members. The measurements are from Lilly and Longair (1984) and Eisenhardt and Lebofsky (1987). It is reasuring that these different samples show the same behavior in the K-band Hubble diagram, with a reasonably small cosmic scatter. However, we do not propose that this sample is homogeneous, complete, or even remotely adequate for cosmological studies. The origin of the IR light in all these objects, and powerful radio galaxies in particular, is still not well understood.

We explore the effects of changes in some of the more important parameters of evolutionary models, i.e., the star formation history, the power-law slope of the IMF, and the mass cutoffs of the IMF. The star formation rate is assumed to decline exponentially (Bruzual μ-models). A simple Friedman cosmology is assumed. The model K magnitude curves were normalized by requiring them to bisect the distribution of data points in the redshift range $0.1 < z < 0.5$ (the aperture corrections are uncertain at lower z's, and the evolutionary and cosmological effects become important for the higher z's).

The most interesting result so far is that whereas the old models fitted the IR data rather well, as indicated in the preliminary study by Spinrad and Djorgovski (1987), the new models do not fit the data as well for the same range of parameters, and show a systematically different behavior. The new models are systematically too bright at large redshifts with respect to the old ones, for the same parameters. Alternatively, one can say that the data are too faint at large redshifts. Such an effect may be produced, e.g., by dynamical evolution (mergers and accretion), for which we do not account.

The $\mu = 0.5$ models can fit the data only in long-time-scale cosmologies, e.g., $H_0 = 50$, $z_{gf} > 10$, and $q_0 \simeq 0$. Steepening of the IMF, and/or biasing towards the *low* mass stars helps, but only slightly. For an "intermediate" set of cosmological parameters, $\mu = 0.1$ models provide a better fit, even though they fail in the optical-UV. Thus, there is still a substantial coupling between the cosmological and evolutionary parameters. We are at this point unable to recommend a good set of evolutionary model parameters.

This illustrates the inherent uncertainty in the state-of-the-art population synthesis models. The problem is tractable to a fundamental calibration difficulty in matching of the input data: the optical-UV spectra are difficult to combine with the near-IR spectra, which are obtained using quite different technologies. Work is now in progress to understand better this process, and produce a more reliable evolution code.

These preliminary results indicate that the potential of the IR Hubble diagram as a cosmological test is less certain than it appeared only a couple of years ago. This conclusion is based upon the variations and ambiguities inherent in the evolutionary models, independent of any problems which may exist with the data. Selection effects, light from nonthermal sources, and other complications can only make the situation worse.

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